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MARS AND THE EARLY SUN.

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Global mean temperatures near 273 K on early Mars are difficult to explain in the context of standard solar evolution models. Even assuming maximum CO_2 greenhouse warming, the required flux is ~15% too low [1]. Here we consider two astrophysical models that could increase the flux by this amount. The first model is a nonstandard solar model in which the early Sun had a mass somewhat greater than today's mass (1.02–1.06 $M_\odot$). The second model is based on a standard evolutionary solar model, but the ecliptic flux is increased due to focusing by an (expected) heavily spotted early Sun.

The relation between stellar mass M and luminosity L for stars near 1 $M_\odot$ is $L \sim M^{4.75}$ [2]. If the Sun's original mass were larger than at present, the early planetary flux would be further increased due to migration of orbits. Isotropic mass loss does not produce a torque on a planet and so angular momentum is conserved. Consequently, semimajor axes increase inversely with mass loss and the flux is proportional to $M^{6.75}$. To increase the flux at Mars by 15% requires that the Sun's mass be $\geq 1.02\ M_\odot$. On the other hand, the flux cannot be so large (1.1× that of the flux at 1 AU today) that Earth would have lost its water [3]. This imposes an upper mass limit of 1.06 $M_\odot$.

Nonclimatic evidence for mass loss of this magnitude might be found in the ion implantation record of meteorites and Moon rocks. Such evidence does exist, but is inconclusive due to uncertainties in exposure times and dating [4,5]. The dynamical record of adiabatic mass loss is also inconclusive. The adiabatic invariance of the action variables implies that the eccentricities and inclinations of planetary orbits remain constant as the semimajor axes increase. The dynamical drag of the wind would have no effect on planets, but would cause a net inward migration of bodies of sizes less than about 1 km [6]. Whether the cratering record is consistent with this dynamical consequence is unclear. Mass loss could also be an additional process contributing to bringing organics into the inner solar system.

A mass loss of 0.1 $M_\odot$ has been suggested as an explanation for the depletion of Li in the Sun by 2 orders of magnitude over primordial values [7]. However, this explanation has been reconsidered by [8], who find that mass loss cannot explain the depletion of Li in Hyades G dwarfs. Although it is generally believed that young G stars are spun down by mass loss, most models are insensitive to the total mass loss required [e.g., 9]: An exception is the model by [10] which predicts a mass loss comparable to our lower limit.

The most promising nonclimatic evidence for main sequence mass loss from the early Sun is the direct observation of similar mass loss from young main-sequence G stars. Detection of stellar mass loss from late dwarfs at the predicted rate (less than $\sim 10^{-10}\ M_\odot\ yr^{-1}$) by optical techniques is generally not possible. However, in one unique case where it could be measured, an outflow 1000× that of the present Sun was found in a K2V dwarf [11]. Recently, huge winds have been reported from several M dwarfs [12]. This technique involves detections over a wide range of radio and millimeter wavelengths and the fact that free-free emission from an optically thick wind has a characteristic spectrum in which the flux is proportional to the 2/3 power of the frequency. As a first step in extending this technique to solar-type stars we have recently used the VLA to obtain the radio emission at 2 and 6 cm in four nearby young G-type stars.

In the second model (ecliptic focusing) we assume standard solar evolution. Young G stars are often observed to be heavily spotted (10–50%). In contrast to mature G stars like the Sun, which typically have only a maximum coverage of ~0.1%, the net effect of star spots on young G stars is to reduce the radiated flux at the location of the spot. Since the total stellar luminosity is determined by nuclear reactions in the core, the flux must increase in regions without spots. Such variations in flux are observed on short (days) and long (years) timescales [13]. These observations measure the anisotropy in the distribution of spots. A more significant effect would be the average increase in the equatorial flux if the time-averaged location of the spotted regions was nearer to the stellar poles than to the equator. This is not the case in today's Sun, but is observed to occur in young stars such as the G2V star SV Camelopardalis, in which there is a ~10% coverage, localized in latitude and longitude, toward one of the poles.

We have investigated a simple model in which polar cap blocking focuses the stellar flux in the equatorial plane. The equatorial flux can be enhanced a maximum of a factor of 2 over the uncapped case. For a time-averaged polar coverage of 10% the equatorial flux enhancement factor is 1.17. Refinements in this model and a review of the relevant observational data will be presented.

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